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## **An overview of glacier lakes in the Western Italian Alps from 1927 to 2014 based on multiple data sources (historical maps, orthophotos and reports of the glaciological surveys)**

Viani, Cristina ; Giardino, Marco ; Huggel, Christian ; Perotti, Luigi ; Mortara, Giovanni

**Abstract:** Since the end of the Little Ice Age (LIA, ca. 1850 AD) a general and progressive retreat of glaciers started in the European Alps, causing important environmental changes in this high mountain region. The appearance of glacier lakes is one of the most evident environmental effects in the Alps as well as in newly deglaciated areas worldwide. In order to understand conditions of formation and reconstruct evolutionary stages of glacier lakes, it is important to collect and analyse a diversity of data from different time periods. Through the analysis of historical topographic maps and digital orthophotos, we identified and digitalized in a GIS environment glacier lakes (and related features) of the Western Italian Alps (Piemonte and Aosta Valley regions) within the LIA maximum extent boundaries. We produced six glacier lake inventories related to six different time steps: 1930s, 1970s, 1980s, 1990s, 2006-07 and 2012. We provided a general overview of the main morphometric, geomorphologic and geographic features of lakes of each time step and preliminary considerations on changes in the number of lakes within the considered time period. The most detailed analysis has been performed over the 2006-07 time step: 214 detected lakes, covering a total area of about  $146 (\pm 1) \cdot 10^4$  m<sup>2</sup>, 3/4 of the lakes measuring less than 6000 m<sup>2</sup> as individual area and a half of the total number less than 2000 m<sup>2</sup>. The mean elevation of lakes was 2776 m a.s.l., 72% being located between 2600 and 3000 m. In general, lakes are localized mainly in the Graian Alps (Rutor-Lechaud, Gran Sassi-Tsanteleina and Gran Paradiso chains) and in the Pennine Alps (Monte Rosa Group). Moreover, in a dedicated database, we collected information (descriptions, photos, maps) about glacier lakes from the reports of the annual glaciological surveys published by the Italian Glaciological Committee (CGI) since 1928. Finally, we reported two cases of glacier lakes at the Tzère Glacier (Monte Rosa Group, Pennine Alps) and at the Ban Glacier (Monte Leone-Blinnenhorn Chain, Lepontine Alps), in order to demonstrate the importance of integrating data from a diversity of sources (historical maps, orthophotos and reports of the glaciological surveys) for better detailed reconstructions of the condition of formation, evolutionary stages and process dynamics of the lake. Results of the present research can contribute to reconstruct and to interpret the spatiotemporal evolution of the phenomenon and to improve the knowledge about the interactions between glacier and related glacier lakes.

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## AN OVERVIEW OF GLACIER LAKES IN THE WESTERN ITALIAN ALPS FROM 1927 TO 2014 BASED ON MULTIPLE DATA SOURCES (HISTORICAL MAPS, ORTHOPHOTOS AND REPORTS OF THE GLACIOLOGICAL SURVEYS)

**ABSTRACT:** VIANI C., GIARDINO M., HUGGEL C., PEROTTI L. & MORTARA G., *An overview of glacier lakes in the Western Italian Alps from 1927 to 2014 based on multiple data sources (historical maps, orthophotos and reports of the glaciological surveys)*. (IT ISSN 0391-9839, 2016)

Since the end of the Little Ice Age (LIA, ca. 1850 AD) a general and progressive retreat of glaciers started in the European Alps, causing important environmental changes in this high mountain region. The appearance of glacier lakes is one of the most evident environmental effects in the Alps as well as in newly deglaciated areas worldwide. In order to understand conditions of formation and reconstruct evolutionary stages of glacier lakes, it is important to collect and analyse a diversity of data from different time periods. Through the analysis of historical topographic maps and digital orthophotos, we identified and digitalized in a GIS environment glacier lakes (and related features) of the Western Italian Alps (Piemonte and Aosta Valley regions) within the LIA maximum extent boundaries. We produced six glacier lake inventories related to six different time steps: 1930s, 1970s, 1980s, 1990s, 2006-07 and 2012. We provided a general overview of the main morphometric, geomorphologic and geographic features of lakes of each time step and preliminary considerations on changes in the number of lakes within the considered time period. The most detailed analysis has been performed over the 2006-07 time step: 214 detected lakes, covering a total area of about  $146 (\pm 1) \cdot 10^4 \text{ m}^2$ ,  $\frac{3}{4}$  of the lakes measuring less than  $6000 \text{ m}^2$  as individual area and a half of the total number less than  $2000 \text{ m}^2$ . The mean elevation of lakes was  $2776 \text{ m a.s.l.}$ , 72% being located between 2600 and 3000 m. In general, lakes are localized mainly in the Graian Alps (Rutor-Lechaud, Gran Sassiere-Tsanteleina and Gran Paradiso chains) and in the Pennine

Alps (Monte Rosa Group). Moreover, in a dedicated database, we collected information (descriptions, photos, maps) about glacier lakes from the reports of the annual glaciological surveys published by the Italian Glaciological Committee (CGI) since 1928. Finally, we reported two cases of glacier lakes at the Tzère Glacier (Monte Rosa Group, Pennine Alps) and at the Ban Glacier (Monte Leone-Blinnenhorn Chain, Lepontine Alps), in order to demonstrate the importance of integrating data from a diversity of sources (historical maps, orthophotos and reports of the glaciological surveys) for better detailed reconstructions of the condition of formation, evolutionary stages and process dynamics of the lake. Results of the present research can contribute to reconstruct and to interpret the spatiotemporal evolution of the phenomenon and to improve the knowledge about the interactions between glacier and related glacier lakes.

**KEY WORDS:** Glacier lakes, Lake inventory, Western Italian Alps, Historical maps, Orthophotos, Glaciological surveys

**RIASSUNTO:** VIANI C., GIARDINO M., HUGGEL C., PEROTTI L. & MORTARA G., *I laghi glaciali delle Alpi Occidentali italiane dal 1927 al 2014: una panoramica basata sull'utilizzo di una molteplicità di fonti (cartografia storica, ortofoto e relazioni delle campagne glaciologiche)*. (IT ISSN 0391-9839, 2016)

A partire dalla fine della Piccola Età Glaciale (PEG, 1850 circa) i ghiacciai delle Alpi sono entrati in una fase di generale e progressivo regresso, causando importanti modificazioni ambientali nelle regioni di alta quota. Uno tra i più evidenti effetti è la comparsa di laghi glaciali nelle zone recentemente deglaciate. Al fine di ricostruire le dinamiche di formazione ed evoluzione dei laghi glaciali è di fondamentale importanza raccogliere e analizzare dati relativi a periodi differenti. Attraverso l'analisi di cartografia storica e di ortofoto è stato possibile individuare e digitalizzare in ambiente GIS i bacini lacustri di origine glaciale delle Alpi Occidentali italiane (Piemonte e Valle d'Aosta) entro i limiti di massima espansione della PEG. Sono stati prodotti sei catasti dei laghi glaciali relativi a sei differenti step temporali: anni '30, anni '70, anni '80, anni '90 (del XX secolo), 2006-07 e 2012. I laghi di ciascun catasto sono stati caratterizzati dal punto di vista morfometrico, geomorfologico e geografico e sono state proposte alcune considerazioni preliminari riguardo le variazioni del numero di laghi nel corso del periodo considerato. È stata effettuata un'analisi di maggior dettaglio per il periodo 2006-07. Sono stati individuati 214 laghi per un'area totale di circa  $146 (\pm 1) \cdot 10^4 \text{ m}^2$ ,  $\frac{3}{4}$  dei laghi hanno una superficie inferiore a  $6000 \text{ m}^2$  e la metà inferiore a  $2000 \text{ m}^2$ . La quota media dei laghi è di  $2776 \text{ m}$

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s.l.m., il 72% di questi è localizzato tra i 2600 e i 3000 m. I laghi sono per la maggior parte situati nelle Alpi Graie (catene del Rutor-Lechaud, Gran Sassi-Tsanteleina e Gran Paradiso) e nelle Alpi Pennine (Gruppo del Monte Rosa). Inoltre sono state raccolte e ordinate, all'interno di un database, informazioni (descrizioni, fotografie, mappe) relative ai laghi glaciali estratte dalle relazioni delle campagne glaciologiche annuali pubblicate dal Comitato Glaciologico Italiano (CGI) a partire dal 1928. Infine sono stati riportati due casi di laghi glaciali al Ghiacciaio di Tzère (Gruppo del Monte Rosa, Alpi Pennine) e al Ghiacciaio di Ban (Catena Monte Leone-Blinnenhorn, Alpi Lepontine) al fine di dimostrare l'importanza di integrare la cartografia storica, le ortofoto e le relazioni delle campagne glaciologiche per ricostruire le dinamiche di formazione ed evoluzione dei laghi. I dati raccolti con la presente ricerca possono contribuire a ricostruire ed interpretare l'evoluzione spaziale e temporale del fenomeno in esame e ad accrescere la conoscenza circa le interazioni tra i ghiacciai e i relativi laghi.

TERMINI CHIAVE: Laghi glaciali, Catasto dei laghi, Alpi Occidentali italiane, Cartografia storica, Ortofoto, Campagne glaciologiche

## INTRODUCTION

Starting from the end of the Little Ice Age (LIA, ca. 1850 AD) a general and progressive shrinkage of the glaciers began in the European Alps, only interrupted by two temporary glacial advances occurred during the years 20s and 70s of the previous century. As a result, alpine glaciers lost about 1/3<sup>rd</sup> of their area between 1850 and 1980 (EEA, 2004). Since the 1980s glacial retreat has been continuous and scientific literature indicates that by the end of the 20<sup>th</sup> century it dramatically accelerated worldwide (Paul & *alii*, 2004; 2011; Zemp & *alii*, 2008). Consequences of ongoing climate warming include the possibility of glacier disappearance within most mountain regions (Zemp & *alii*, 2006). As shown by recent studies (Salvatore & *alii*, 2015; Smiraglia & *alii*, 2015) also Italian glaciers are experiencing this general withdrawal trend, some are fractioning and other disappearing.

The disappearance of glacier masses produced substantial modifications in high mountain environments: new alpine geomorphological landscapes are forming, new opportunities and risks are appearing with. One of the most evident geomorphological effect is the formation of glacier lakes in recently deglaciated areas (Linsbauer & *alii*, 2009). Most of these new lakes are located within "basins" due to bedrock depressions or moraine dams (Frey & *alii*, 2010a; Emmer & *alii*, 2015). During glacier retreat, the over deepened parts of the glacier bed become exposed and, in some cases, they can be filled by water. As a consequence, progressive retreat of glaciers is followed by increasing number of new glacier lakes (Paul & *alii*, 2007; Salerno & *alii*, 2014; Carrivick & Tweed, 2013) and by significant morphological changes in the existing ones.

Glacier lakes, especially in densely populated mountain regions such as the European Alps, are of considerable significance, other than for geomorphological significance, due to several reasons: 1) their potential economic value (e.g. for hydropower production and tourism activities); 2) their environmental relevance for high mountain ecosystems and biodiversity; 3) the associated potential risks (e.g. lake outburst and consequent flood) (NELAK, 2013);

4) their link with climate change, in fact, their evolution reflects climatic fluctuations (Salerno & *alii*, 2014).

For all these reasons, regional inventories of glacier lakes are considered essential sources for both first and general overview of the phenomenon and for providing basic data for further applied purposes (Carrivick & Tweed, 2013).

Regional studies about glacier lakes of the European Alps have been carried out in Switzerland (Huggel & *alii*, 2002; Frey & *alii*, 2010b; Paul & *alii*, 2007) and in Western Austria (Emmer & *alii*, 2015), in view of assessing associated hazard and risk potentials. Concerning the Italian Alps, regional studies in the Ortles-Cevedale mountain group (Salerno & *alii*, 2014) and in Lombardia region (Galluccio, 1998) has to be mentioned.

The overall aim of our work is to contribute to enhance knowledge on alpine glacier lakes by focusing the attention on the Western Italian Alps (Piemonte and Aosta Valley regions) and by providing data covering a relatively long time period: from the beginning of the 20<sup>th</sup> century until now.

Main objectives of this study are:

- to produce a set of inventories of glacier lakes within the study area, related to different time periods;
- to give a general overview of the morphometric, geomorphologic and geographic features of the lakes of each time period;
- to create a dedicated database and to test an operational routine for collecting information (reports, photos, maps, etc.) about glacier lakes;
- to demonstrate, through few cases, the importance of integrating different sources of data for the reconstruction of the formation condition, evolutionary stages and process dynamics of glacier lakes;
- to provide preliminary considerations on changes in the number of glacier lakes within the study area and the considered time period.

## STUDY AREA

The study area covers the Western Alps of Italy, from the Maritime to the Lepontine Alps, within the mountain territories of Piemonte and Aosta Valley regions (fig. 1). It includes main glaciated areas of massifs such as Gran Paradiso (4061 m), Monte Bianco (4808 m), Monte Rosa (P.ta Gnifetti, 4559 m) and Monte Leone (3553 m).

Within the study area, the first systematic inventory of Italian glaciers (CGI, 1961) developed by the Italian Glaciological Committee in cooperation with the National Research Council, reported glaciers covering a total area of 237.8 km<sup>2</sup>.

According to Smiraglia & *alii* (2015), present glaciers of the Western Italian Alps cover a cumulative area of 162.65 km<sup>2</sup> (44% with respect to the whole Italian glacial coverage). Concerning recent glacial withdrawal in Italy, the Piemonte Region shows the strongest decrease in glacial area between the 1960s and the present time (more than 40% of its previous coverage) and the Aosta Valley (the region with largest glaciated area of Italy) has given the largest contribution (24%) to the national

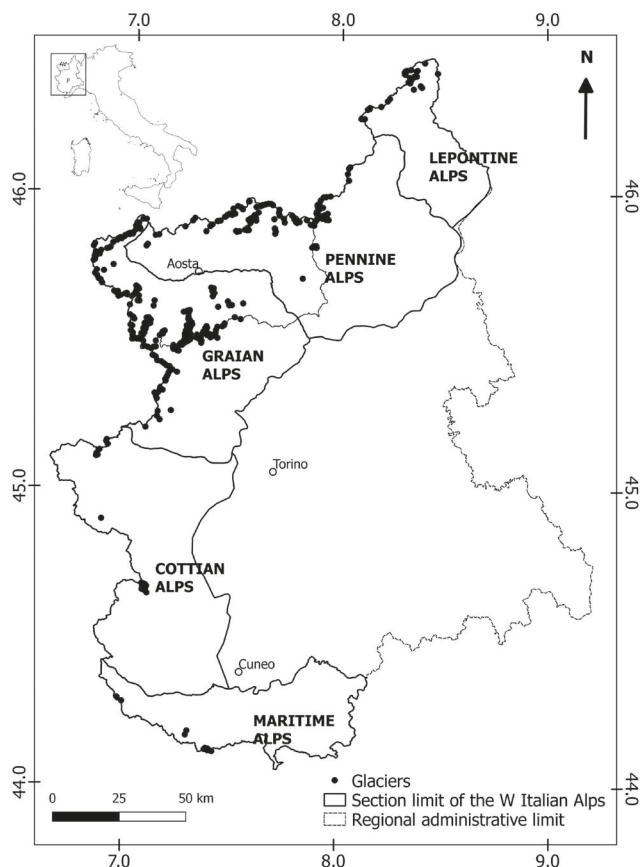


FIG. 1 - Section of the Western Italian Alps according to the ISMSA-SOI-USA (Marazzi, 2005) and location of glaciers according to the Italian Glacier Inventory (CGI, 1961).

glacier loss (30.5%). Lucchesi & *alii* (2014) calculated an area reduction of 77.8% between 1850 and 2006 for glaciers in the Western and South-Western Piedmont Alps. Salvatore & *alii* (2015) confirmed and highlighted the current trend of glacier extinction, areal reduction and fragmentation.

Newly exposed areas from glaciers withdrawal offer suitable conditions for glacier lakes formation (Diolaiuti & *alii*, 2012). Specific cases on glacier lakes of the study area have been reported since the beginning of the 20<sup>th</sup> century, e.g.: Galambra (Peretti, 1935) in the Cottian Alps, Locce (Haeberli & Epifani, 1986; Tropeano & *alii*, 1999) in the Pennine Alps, Rutor (Dutto & Mortara, 1992) in the Graian Alps, Miage (Diolaiuti & *alii*, 2006) in the Graian Alps, Belvedere (Mortara & Tamburini, 2009) in the Pennine Alps, Rocciamelone (Vincent & *alii*, 2010) in the Graian Alps. The above mentioned studies mainly focus on potentially hazardous conditions related to the presence of glacier lakes. Moreover, a comprehensive database containing information about events of Glacier Lake Outburst Flood (GLOF) in Europe has been realized, in the framework of the GlacioRisk project (<http://www.nimbus.it/ghiacciai/glaciorisk.htm>): it includes data from the Western Italian Alps. Finally, in the framework

of the GlaRiskAlp project (<http://www.glariskalp.eu/>), an inventory of lakes formed since the 1980s has been produced for a sector of the Western Alps (Italy and France) that is only a part of the study area investigated in the present work.

As a matter of fact, our study of glacier lakes in the Western Italian Alps is intended to fill the gaps within results of previous studies and to offer a comprehensive analysis on glacier lakes over a long time period (1927-2014), based on multiple data sources (historical maps, orthophotos and reports of the glaciological surveys).

## DATA SOURCES

### *Historical maps*

The Italian Military Geographical Institute (Istituto Geografico Militare Italiano, IGMI) produced the first issue of the official topographic map of Italy at the end of the 19<sup>th</sup> century at a scale of 1:25,000. Successive updates have been published during the 20<sup>th</sup> century. Those maps, with contour lines and relevant symbols also for high mountain sectors, can be used for geothematic mapping purposes within the glacial environment (Carton & *alii*, 2003). Also previous historical cartographic documents such as the “Dufour”, “Sigfried” and “Stati Sardi” maps (reviews on Aliprandi & Aliprandi, 2005) could be important sources of qualitative information about geomorphological features, such as the presence or absence of glacier lakes, even if they don’t allow precise extraction of shape and area of lakes. Nevertheless, the comparison of topography of the same area on different maps’ edition could be very useful for multi-temporal geomorphological change detection, especially for glaciological purposes (Carton & *alii*, 2003). Pelfini (2004) showed some examples of studies on glacier lakes through the detection and analyses of different phases of their evolution represented in the historical official map of Italy by IGMI.

For the above mentioned reasons, first actions of our study were the collection, digitalization and georeferencing of topographic maps of the IGMI (1:25,000 in scale) covering the study area and published during the 20<sup>th</sup> century (tab.1).

### *Orthophotos*

High resolution orthophotos are proven to be important data sources for glaciological purposes (Salvatore & *alii*, 2015; Smiraglia & *alii*, 2015). The National Geoportal of the Italian Ministry of Environment and Protection of Land and Sea freely provides digital orthophotos, through the Web Map Service (WMS: <http://www.pcn.minambiente.it/GN/accesso-ai-servizi/servizi-di-visualizzazione-wms>).

Aerial imagery is characterized by a high resolution (ranging from 1:5,000 to 1:10,000 in scale) and usually shows a low or absent cloud coverage. Photos are taken mainly in the summer period when also the snow cover is low or absent.

The analyzed orthophotos have been surveyed in: 1987-1989, 1994-1998, 1998-1999, 2006-2007 and 2012 (tab.1).



TABLE 1 - List of the data sources, related cartographic parameters and error.

Period	Source of data	Scale factor	GSD (m)	$\sigma_{xy}$ (0,2 of the scale factor)	CE95
1929-34	IGMI topographic maps	25,000		5	12.2
1966-70	IGMI topographic maps	25,000		5	12.2
1987-89	Orthophotos B/W	10,000	1	2	4.9
1994-98	Orthophotos B/W	10,000	1	2	4.9
1998-99	Orthophotos color	10,000	1	2	4.9
2006-07	Orthophotos color	5,000	0.5	1	2.4
2012	Orthophotos color	5,000	0.5	1	2.4

### Reports of the annual glaciological surveys

Thanks to the activities of the Italian Glaciological Committee (CGI), the systematic monitoring of Italian glaciers has never been interrupted since it started on 1911. During the annual glaciological surveys, carried out at the end of the ablation summer season, volunteers collect measures, photos and observations of the glaciers and surrounding areas in the Italian Alps. Since 1928, the reports are published in a dedicated section of the CGI Bulletin (CGI, 1928-1977; 1978-2015). As CGI members, authors of this paper cooperated with the digitalization effort of the Italian Glaciological Committee to offer free availability of the annual glaciological surveys on the website of the CGI (<http://www.glaciologia.it/i-ghiacciai-italiani/le-campagne-glaciologiche/>).

### METHODS

We selected historical maps and digital orthophotos for being used as base layers in an open source GIS (Geographic Information System, Q-gis®) environment. We detected glacier lakes, with a surface area greater than 100 m<sup>2</sup>, and manually digitized lake outlines on computer screen. As buffer polygons for lakes detection, we used the LIA glaciers extent produced in the framework of the GlaRiskAlp project, available as .kml file from the project website ([http://www.glariskalp.eu/?it\\_inventario-delle-estensioni-attuali-e-passate-dei-ghiacciai,9](http://www.glariskalp.eu/?it_inventario-delle-estensioni-attuali-e-passate-dei-ghiacciai,9)).

A set of attributes have been assigned to each lake: area, perimeter, elevation, geographic coordinates of the barycenter and detection year. Furthermore every lake has been classified according to the type of dam, as: bed-rock-dammed, moraine/debris-dammed and ice-dammed. The interpretation was supported by the use of TerraExplorer virtual globe. Finally, each lake has been associated to the corresponding alpine supergroup according to the International Standardized Mountain Subdivision of the Alps, ISMSA-SOUSA (Marazzi, 2005).

The large variety of the data sources we used (a set of 7 different maps and orthophotos) required consideration of the accuracy of derived data; in particular the map reading error ( $\sigma_{xy} = 0.2$  mm of the scale factor) has been considered.

In fact, the level of detail of a topographic map and/or a orthophoto is determined by its scale factor. We decided on this kind of error approach in order to maintain comparable the planimetric accuracy among different data sources. The final CE95 (Circular Error) has been calculated according to FGDC (1998), AA.VV. (2009) and ASPRS (2014), which considered the 95% of the lake mapping error. Final CE95 values is equal to a supposed real map reading error of 0.49 mm of the scale factor that includes also the uncertainty of manual delimitation. Thus the area precision for each lake has been evaluated by buffering the lake perimeter using the CE95. The overall error of the whole Western Italian Alps lake coverage for each time step (tab. 2) has been assessed by using the root of the squared sum of all the buffer areas, as suggested by Citterio & alii (2007) and Minora & alii (2016).

In addition, we analysed the complete set of annual glaciological surveys published by the CGI in the time interval 1927-2014 to seek further information (description, measures, photos, maps, etc.) on glacier lakes in the Western Italian Alps. We stored and organized all collected data into a dedicated database; other than description text, every single record includes information on: name of the glacier, year of the observation, issue and page of the CGI Bulletin, author of the report. The database represents a useful tool for confirming, integrating and completing results obtained by means of maps and orthophotos analysis and interpretation.

### RESULTS

Here we present a summary of the results obtained by the analysis and interpretation of topographic maps and orthophotos and by the search of information on glacier lakes on the CGI Bulletin, as described before.

We produced six glacier lake inventories, related to six different time steps: 1930s, 1970s, 1980s, 1990s, 2006-07 and 2012. A general overview of the morphological characteristics of glacier lakes within each of the considered time steps is presented in tab. 2. A short description of the results of each inventory is presented below, including numerical data such as the total number of mapped glacier lakes, total lake covered area, altitudinal extent and description of their geographic distribution and the main types of lake.

#### 1930s

The analysis of IGMI topographic maps dated from 1929 to 1934 has produced an inventory containing 43 lakes. They covered a total area of  $55.58 (\pm 4) \cdot 10^4$  m<sup>2</sup> with a median area of  $0.42 \cdot 10^4$  m<sup>2</sup>. The lakes spread out between 1868 m and 2996 m of elevation, their mean elevation was 2692 m a.s.l.

Concerning their geographic distribution about half of mapped lakes (20 over 43 individuals, 47% of the sample) were located in the Rutor-Lechaud Chain (Graian Alps), 8 lakes (19%) in the Gran Sassiere-Tsanteleina Chain (Graian Alps) and the other 15 lakes (34%) spread out from the Ambin-Ciamarella Chain (Cottian and Graian Alps) to the Monte Rosa Group (Pennine Alps). No lakes have been identified in the Lepontine Alps.

TABLE 2 - General summary of the morphometric characteristics of glacier lakes for the six time steps

Year		1930s	1970s	1980s	1990s	2006-07	2012
Number of lakes (N)	Total	43	66	133	178	214	186
Elevation (m a.s.l.)	Mean	2692	2704	2751	2786	2776	2747
	Max	2996	2989	3122	3447	3346	3270
	Min	1868	1868	1868	1868	1868	1868
Perimeter (10 <sup>4</sup> m)	Median	0.03	0.03	0.02	0.02	0.02	0.02
Lake area (10 <sup>4</sup> m <sup>2</sup> )	Median	0.42	0.38	0.27	0.2	0.2	0.24
	Total	55.58 ± 4	87.64 ± 5.18	128.51 ± 2.58	133.37 ± 2.63	145.94 ± 1.39	139.58 ± 1.37

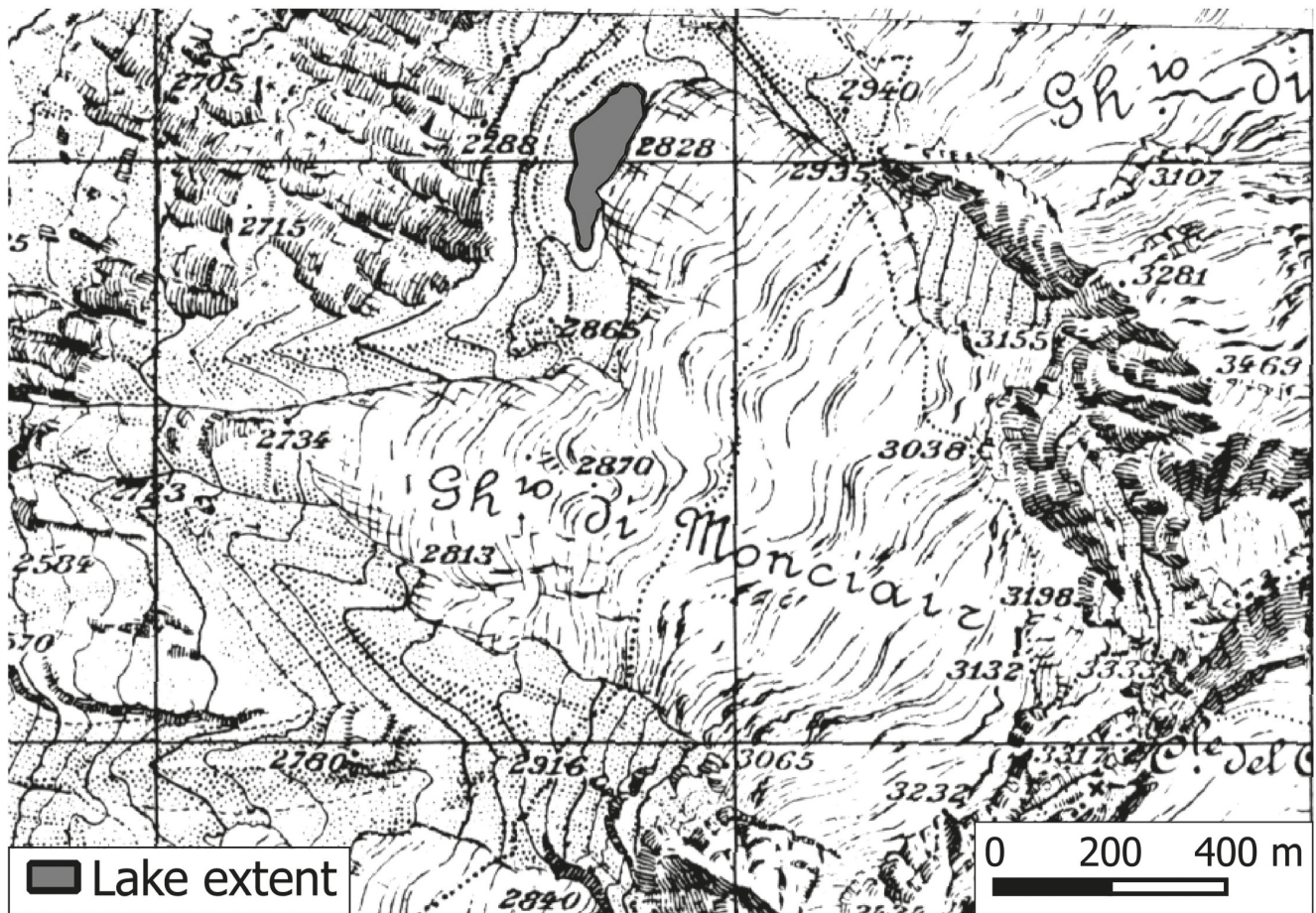


FIG. 2 - Monciair Glacier (Gran Paradiso Chain, Graian Alps) and his proglacial lake on the IGM sheet 41 II NO, Ceresole Reale (1931).

Concerning the lake types, the great majority were proglacial lakes located in bedrock overdeepenings (33 individuals, 77% of the sample), some being dammed by moraines (10 individuals, 23% of the sample). Only 4 lakes (9% of the total sample) were in contact with the glacier front, such as the proglacial lake at the Monciair Glacier, Gran Paradiso Chain, Graian Alps (fig. 2).

Almost all the lakes identified on the first edition of the IGMI topographic map have been recognized also in fur-

ther maps and orthophotos, thus possibly surviving about 80 years. Only 2 lakes constitute an exception: they were mapped in the 1930s but not recognized in the following documents.

#### 1970s

The analysis of the successive edition of the IGMI map (issued between 1966 and 1970) allowed identification of 66



glacier lakes. The total area covered by the lakes was  $87.64 (\pm 5.18) \cdot 10^4 \text{ m}^2$  (median  $0.38 \cdot 10^4 \text{ m}^2$ ). The elevation ranged from 1868 m to 2989 m, with a mean altitude of 2704 m a.s.l.

Lakes were located mainly in the Rutor-Lechaud Chain (27 lakes, 41% of the sample) and in the Monte Rosa Group (20 lakes, 30% of the total sample), they are the newly formed lakes at the Rutor and Valtournanche glaciers. They were proglacial lakes (78% dammed by the bedrock and 22% by moraine).

#### 1980s

The observation of the orthophotos related to the 1987-89 national flight allowed to identify 133 glacier lakes within the study area. Lakes covered a total surface of  $128.51 (\pm 2.58) \cdot 10^4 \text{ m}^2$  (median  $0.27 \cdot 10^4 \text{ m}^2$ ). Their altimetric distribution ranged between 1868 m and 3122 m, their mean elevation was 2751 m a.s.l.

The majority of lakes were located in the Rutor-Lechaud Chain (32%), Gran Sassi-Tsanteleina Chain (13%), Monte Rosa Group (12%) and Gran Paradiso Chain in the Graian Alps (11%).

Lakes were proglacial lakes dammed by the bedrock (73%) or by moraine (26%). A supraglacial lake was detected on the surface of the Schiantala Glacier, a debris-covered glacier in the Corborant-Tenibres-Enciastraia Chain (Maritime Alps).

#### 1990s

Concerning the time period between 1994 and 1999, we mapped 178 glacier lakes covering a total area of  $133.37 (\pm 2.63) \cdot 10^4 \text{ m}^2$  (median  $0.20 \cdot 10^4 \text{ m}^2$ ). Their minimum elevation was 1868 m, the maximum 3447 m and the mean 2786 m a.s.l.

Glacier lakes were located mainly in the Rutor-Lechaud Chain (30%), in the Gran Sassi-Tsanteleina Chain (13%), in the Gran Paradiso Chain (12%) and in the Monte Rosa Group (10%). They were mainly proglacial lakes filling bedrock overdeepenings (75%) and dammed by moraine or debris (26%). There were also few cases of supraglacial lakes (2%) located on the surface of debris covered glaciers.

#### 2006-07

High quality of the orthophotos allowed grater data collection and more detailed analysis related to the years 2006-07. We identified 214 glacier lakes, with a total area of  $145.94 (\pm 1.39) \cdot 10^4 \text{ m}^2$  (median  $0.20 \cdot 10^4 \text{ m}^2$ ). Lake area varies between a minimum of about  $0.01 \cdot 10^4 \text{ m}^2$  to a maximum of  $12 \cdot 10^4 \text{ m}^2$ . Half of the lakes were characterized by an area smaller than  $0.2 \cdot 10^4 \text{ m}^2$  and 76% of the lakes have a surface area less than  $0.6 \cdot 10^4 \text{ m}^2$  (fig. 3).

The elevation varies between 1868 m and 3346 m and the mean value is 2776 m. In the years 2006-07, 72% of the lakes were located between 2600 and 3000 m a.s.l (fig. 4).

Glacier lakes of the 2006-07 inventory were localized mainly in the Rutor-Lechaud Chain (27%), in the Gran Sassi-Tsanteleina Chain (15%), in the Gran Paradiso Chain (13%) and in the Monte Rosa Group (12%).

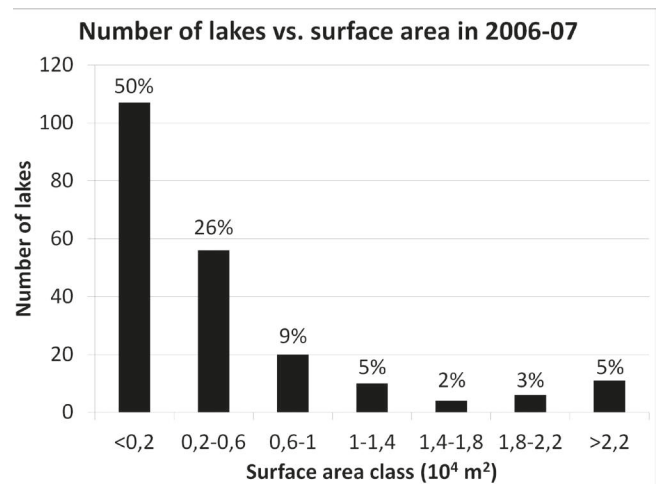


FIG. 3 - Frequency distribution of glacier lakes in 2006-07 with respect to their surface area.

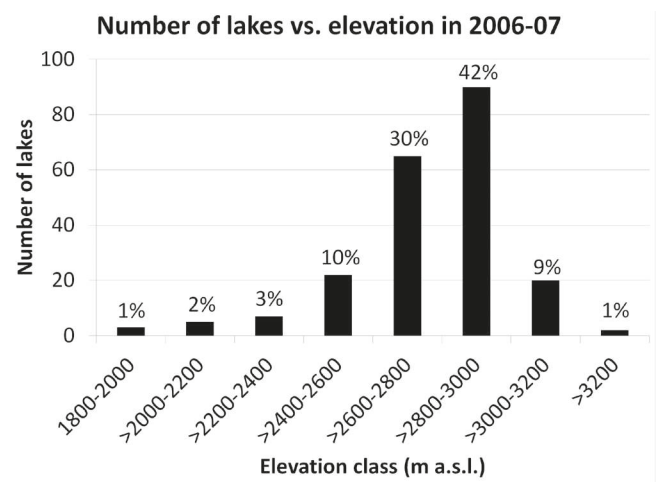


FIG. 4 - Frequency distribution of glacier lakes in 2006-07 with respect to their elevation.

From South to North, the mountain arch of the Western Italian Alps encompasses approximately 250 km (only about 77 km from West to East). Within the 2006-07 sample of glacier lakes in the Western Italian Alps, we analysed their geographical distribution by considering elevation as a function of latitude (fig. 5). We found that glacier lakes in the Maritime Alps were located around 2600 m a.s.l.; in the Cottian Alps between 2800 and 3000 m of elevation, with the exception of a lake in the Monviso Group located at 3270 m a.s.l.; in the Graian Alps, they were mainly located between 2400 and 3200 m, with the exception of the lakes at the Miage Glacier located at much lower elevation (about 1900 m); in the Pennine Alps, there was a wide range of elevations of glacier lakes ranging from 2100 m (lakes on the Belvedere Glacier) to a maximum of 3300 m a.s.l.; in the Lepontine Alps, glacier lakes have been surveyed between 2300 and 2800 m a.s.l.



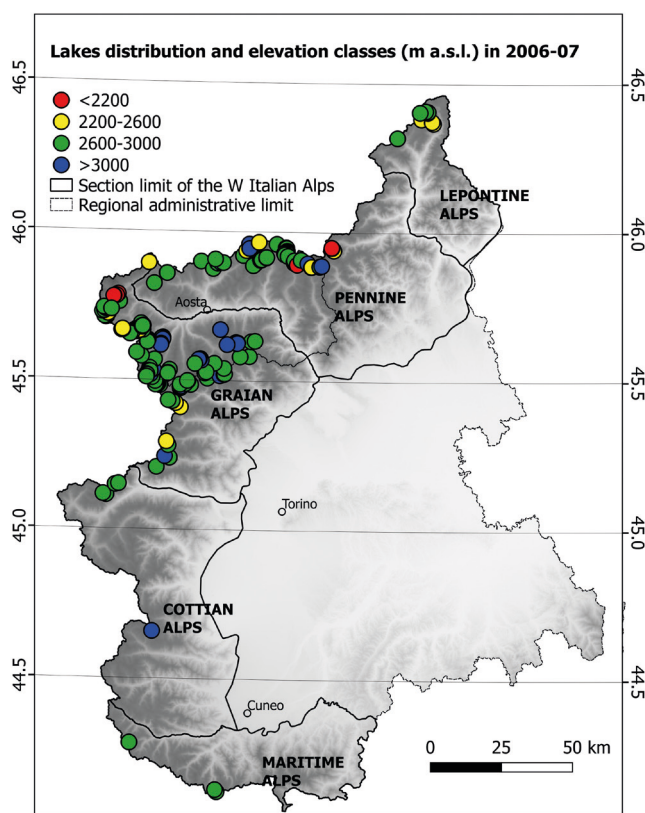


FIG. 5 - Maps of the geographical and altitudinal distribution (m a.s.l.) of glacier lakes in 2006-07.

2012

On the set of orthophotos dated 2012, 186 glacier lakes have been identified. Lakes covered a total area of  $139.58 (\pm 1.37) \cdot 10^4 \text{ m}^2$  (median  $0.24 \cdot 10^4 \text{ m}^2$ ). They were located between 1868 m and 3270 m of elevation (mean value: 2747 m a.s.l.).

Glacier lakes were located in the Rutor-Lechaud Chain (27%), in the Gran Paradiso Chain (14%), in the Gran Sassiere-Tsanteleina (12%) and in the Monte Rosa Group (12%).

Concerning the lake types we found: 69% dammed by the bedrock, 26% dammed by moraine or debris and 5% of supraglacial lakes on debris-covered glaciers such as the Miage Glacier.

#### *Database of the reports of the glaciological surveys concerning glacier lakes*

We stored in a dedicated database the information on glacier lakes derived from the reports of the annual glaciological surveys published by the CGI. We inserted 762 records from reports of the time period 1927-2014. Considered reports are short or long description of glacier lakes observed by the volunteers of the CGI during their survey at glaciers, sometimes associated with measurements, photos and maps of lakes.

The number of reports on glacier lakes for each year

varies depending on the total number of surveyed glaciers; for example, during the Second World War only few glaciers were visited, therefore also the number of reports on lakes was low. Starting from the beginning of the 21<sup>st</sup> century the number of reports increased (fig. 6). This fact could be attributed both to the increase in the number of glacier lakes and to the greater attention of the volunteers to this kind of phenomenon.

We found information about glacier lakes related to 129 glaciers of the Western Italian Alps, 24 of them have more than 10 years of reports regarding the presence of lakes in their surroundings (tab. 3). For example, glaciers

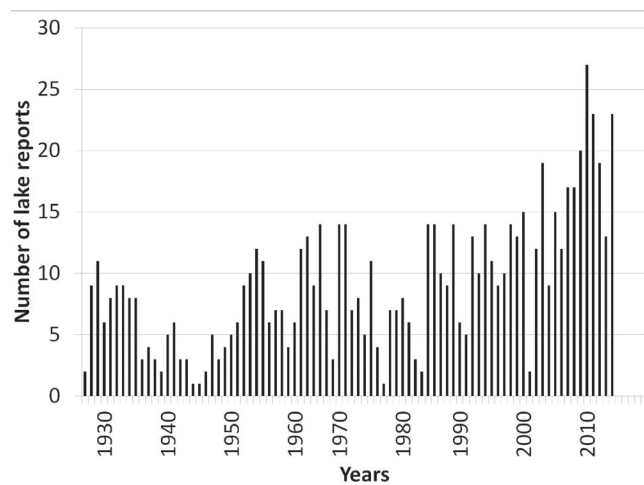


FIG. 6 - Number of reports regarding lakes stored in the database for each annual glaciological survey.

TABLE 3 - Glaciers with more than 10 records concerning their lakes.

Glacier	N of reports	First report	Last report
Pera Ciaval	12	1991	2014
Bessanese	24	1928	2013
Mulinet Sud	10	1957	2012
Sengie Sett.	14	1971	2014
Lauson	14	1931	2007
Monciair	12	1959	2005
Lavassey	24	1928	2014
Soches-Tsanteleina	11	1951	2011
Goletta	31	1948	2011
Rutor	42	1928	2014
Valaisan	10	1951	2014
Chavannes	15	1952	2002
Miage	34	1929	2014
Cherillon	11	1943	1981
Valtournanche	30	1931	1980
Lys	16	1970	2014
Indren	11	1953	2014
Locce Nord	34	1934	2013
Belvedere	13	1993	2014
Gemelli di Ban	10	1961	1987

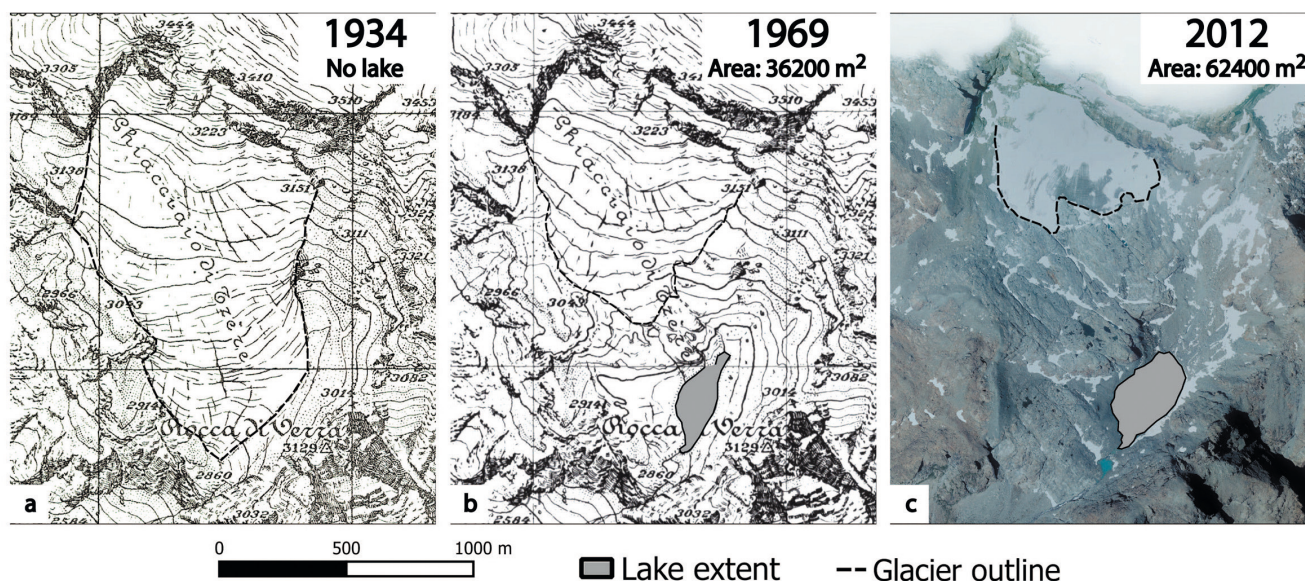


FIG. 7 - Tzère Glacier (Monte Rosa Group, Pennine Alps) on two successive editions of the IGM sheet 29 I SO, Saint Jacques (1934 and 1969) and in the 2012 orthophoto (Imagery: Italian National Geoportal).

of Rutor (42), Miage (34), Locce Nord (34), Goletta (31) and Valtounanche (30) have a series of more than 30 years of reports regarding the presence of lakes. Having such long series of information allows to reconstruct the evolutionary stages of this dynamic system during a long time period (eg.: the first notice about lakes at the Rutor Glacier dated 1928 and the last one 2014).

## DISCUSSION

### *Examples of lakes formation and evolution: the importance of integrating different data sources*

In order to demonstrate the usefulness of integrating historical maps, orthophotos and reports of the glaciological surveys, we present two examples regarding the formation and successive evolution of glacier lakes.

The first example (fig. 7) concerns the Tzère Glacier located in the Ayas Valley (Monte Rosa Group, Pennine Alps, Aosta Valley). In fig. 7a the glacier reached the rock step at about 2860 m a.s.l.; in 1969 (fig. 7b) the glacier front retreated, leaving an overdeepened area occupied by a newly formed lake. In 1976, the glaciological survey reported: “Below the western slopes of the Rocca di Verra it has formed a periglacial lake (2900 m a.s.l.) of about 250 x 80 m”. The lake increased in size and survived until 2012 (fig. 7c).

The second example is represented by the Ban Glacier in the Formazza Valley (Monte Leone-Blinnenhorn Chain, Lepontine Alps, Piemonte). In 1974, the operator of the CGI reported: “The glacier has not been surveyed since 1971. The glacier front “plunged” in a little lake dammed by a huge moraine”. The successive evolution of the lake could be reconstructed by the orthophotos sequence (fig. 8), where the progressive retreat of the glacier and the consequent enlargement of the lake is clearly recognizable.

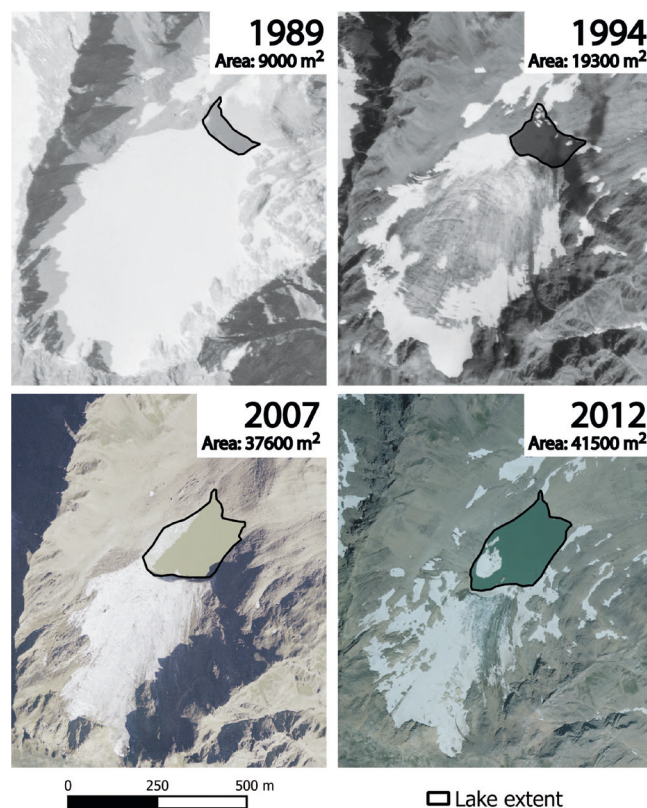


FIG. 8 - Formation and evolution of a proglacial lake at Ban Glacier (Monte Leone-Blinnenhorn Chain, Lepontine Alps) between 1989 and 2012 (Imagery: Italian National Geoportal).



### Glacier lake inventories by topographic maps and orthophotos: advantages and limitations

Our analyses and interpretation of topographic maps and aerial orthophotos allowed to identify, map and measure glacier lakes within different time steps. The integration of different data sources has been necessary in order to cover a long time period, as it has been required in this study of the post-LIA modification of glaciated mountains of the Western Italian Alps.

Before the onset of aerial photogrammetry techniques, historical maps represent the only available data for cartographic purposes. Our study demonstrated the usefulness of historical maps: we identified and mapped 43 and 66 lakes in the 1930s and in the 1970s respectively, despite the map nominal scale being 1:25,000. Moreover, for some selected cases we have been able to reconstruct the condition of formation and the evolutionary stages of glacier lakes (e.g.: Tzère Glacier).

However, it is important to take into account qualitative and quantitative errors that can result from historical maps used as data sources. A historical map is a product of successive activities: direct topographic measurements, maps production and successive cartographic updates. For all these reasons it is difficult to know if the map we are analyzing is the real representation of our study area in a certain time. Consequently, from a qualitative point of view, the real presence or absence of lakes could not be really certain, considering also their ephemeral nature. Furthermore, the difficulty in map symbols interpretation, sometimes makes doubtful lake existence.

Concerning quantitative errors, digitizing lake outlines using historical maps as base layer leads to a  $\pm 6\text{--}7\%$  total areal error in the 1930s and 1970s. This must be taken into account once doing comparison of lakes total area through time.

On the contrary, orthophotos, due to their image GSD

(Ground Sample Distance) minor than 1 m, allowed an accurate identification and digitalization of lakes. For example, during 2006-2007 the availability of high resolution images all over the study area allowed detailed dimensional characterization also of small lakes ( $<1000\text{ m}^2$ ) that represent 30% of the population. The total areal error in this case is less than  $\pm 1\%$ .

The main practical problems we experienced in orthophotos analysis are: the digitalization of lakes that appear partially or totally frozen, despite photos were mainly acquired during summer; shadowed areas due to the acquisition flight time and relative elevation; the discrimination between lakes and flooded areas.

### Consideration on changes in the number of glacier lakes from the 1930s to 2012

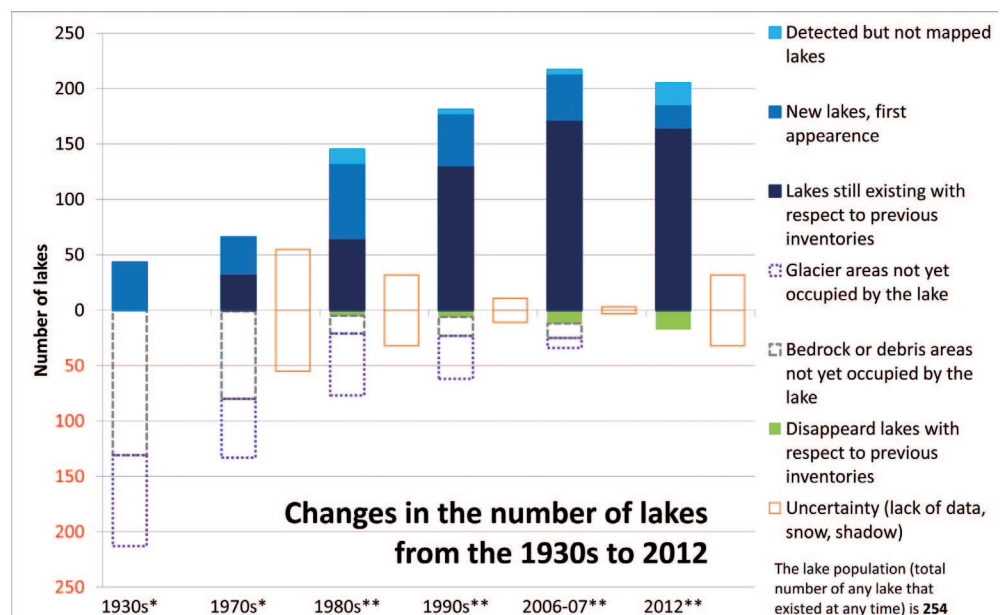
The total amount of mapped lakes (lake population) during the period 1930s-2012 is 254, but they have never been surveyed all in the same time step.

We performed an analysis on the causes of the changes in the total amount of lakes in each time step (fig. 9). The aim is to understand what happened to glacier lakes during the considered period.

We observed on the maps and on the orthophotos all the areas where lakes have been detected. For each time step we classified our observation in 7 different categories. The first four classes are directly related to the lakes, which can be distinguished in:

- 1) "survived" lakes with respect to previous inventories (dark blue bar);
- 2) new lakes, those who appeared for the first time (light blue bar);
- 3) detected but not mapped lakes, those who can be identified on the orthophotos but can't be precisely mapped because partially covered by snow or ice (turquoise bar);

FIG. 9 - Changes in the number of glacier lakes from the 1930s to 2012. Data were derived from \* historical maps and \*\* orthophotos. The lower part of the y-axis (red numbers) represents upcoming and/or disappeared lakes.



4) disappeared lakes with respect to the previous inventories (green bar).

Lakes not classified in previous classes are those who were not yet appeared within the considered time step. By a retrospective analysis, we observed their supposed location and classified the related areas in 2 more categories:

5) areas occupied by the glacier (violet dotted line), and

6) glacier-free areas (bedrock or debris) (grey dotted line).

A further category has been introduced, namely:

7) “uncertainty” (identified by the orange line), it has been defined as the number of lakes that we are not able to understand if they are present or not within the considered time step. This number could be distributed among the previous classes keeping in mind that the total lake population is always 254. The uncertainty is due to lack of data (this is the case only of the 1970s IGMI map), snow cover (related to the acquisition flight date) or shadowed areas (related to the acquisition flight time and relative elevation).

Starting from the 1930s we can notice that only 17% of the total amount of lakes was present in that period.

Considering the 1970s inventory, only 33 of the 43 detected lakes within the 1930s time step have been identified. Only for one of them we could verify the real disappearance on the IGMI map of the 1970s. Considering the other 9 lakes, a lack of data prevented further interpretation: in fact none updated version of the IGMI map for the 1970s is available for the Marittime Alps, the Gran Paradiso Group and the Lepontine Alps. Since we don't have data for the 22% of the total amount of lakes (represented with the orange line), therefore they could be survived, disappeared or appeared with respect to the previous inventory. However, we noticed an increase in the number of lakes: 33 new lakes formed, 13 of them appeared after a glacier retreat stage happened between the 1930s and the 1970s.

In the 1980s time step, lakes doubled with respect to the previous inventory: 65 new lakes appeared. Starting from the 1980s we introduced the third category of lakes, those who can be identified on the orthophotos but can't be precisely mapped, because partially covered by snow or ice. In the 1980s, they represent the 5% (12 lakes) of the total population.

It is interesting to note the numerical difference between the 1970s and the 1980s in the “areas occupied by the glacier” bar: this means that two lakes existed in the 1970s but disappeared in the 1980s. In particular they are two proglacial lakes appeared in the 1970s at the front of the Lys Glacier, as indicated by both historical maps and reports of the glaciological surveys (CGI, 1971-1975). In the 1980s these two lakes disappeared, because their location is occupied by advancing glacier front.

The 13% of the lakes were not detectable because of the presence of snow.

The increase in the number of lakes continues in the 1990s: 131 lakes survived and 47 new lakes formed. Only few lakes (6) disappeared, probably because of infilling processes; also not detectable lakes are few (11).

In 2006-07 the maximum number of detected lakes was reached (217 lakes, which include mapped lakes and detected but not mapped lakes). The majority of new lakes (62%)

were located in areas previously occupied by glaciers, their appearance is consequently due to glacier retreat. 12 lakes disappeared in 2006-07, the observation of the orthophotos allowed to understand the causes: they were filled in by sediment.

The 2006-07 orthophotos are those with the best quality among all data sources: only in 3 cases we could not assert if the lake was present or not because of snow cover. The 99% of the investigated areas is clearly visible. This fact makes this inventory the most accurate among the six inventories.

Concerning 2012 time step, there is a slight decrease in the total number of detected lakes (205 lakes against 217 lakes in 2006-07). We can make some hypothesis about the causes. Certainly the number of disappeared lakes increased with respect to the previous inventories: 17 lakes disappeared, mainly because of infilling processes, and there are also 6 cases of ephemeral epiglacial lakes, formed on the surface of debris-covered glaciers in 2006-07 (Miage and Belvedere Glacier) and emptied in 2012. It is also clear that in the first half of July 2012, when the aerial photographs were taken, the snow cover was considerably extended on the investigated areas (13%); this prevented to understand if some lakes (32) survived or disappeared.

## CONCLUSIONS

Based on the analysis of historical topographic maps and aerial orthophotos, we produced six different glacier lake inventories related to the 1930s, 1970s, 1980s, 1990s, 2006-07 and 2012 in the Western Italian Alps. We provided a general overview of the main morphometric, geomorphologic and geographic features of the lake population of each time step.

By means of the bibliographic research in the reports of the glaciological surveys published since 1928 in the Bulletin of the CGI, we also collected and stored in a dedicated database information about glacier lakes within the study area. Starting from the beginning of the 21<sup>st</sup> century, we recognized an increase in the number of reports regarding glacier lakes, probably due to both the increase in the number of glacier lakes and the greater attention to this phenomenon.

We reported detailed description of two cases of glacier lakes (at Tzère and Ban glaciers) in order to demonstrate the importance of both historical maps and orthophotos for the reconstruction of the condition of formation and the successive evolutionary stages of lakes. We also encouraged the integration of this data with the reports of the glaciological surveys and the material collected by the Italian Glaciological Committee that are proved to be important sources of information, especially when other data sources are lacking.

Moreover, we carried out a preliminary analysis on changes in the number of lakes from the 1930s to 2012. This allowed some considerations both on quality of data sources and on environmental conditions of lake forming and disappearing. Both are relevant conditioning factors controlling the total number of lakes. The multi-temporal and multisource approach allowed better understanding



of what happened to glacier lakes during the considered time period. By a step-by-step comparison of single time constrained geolocated features (glacier lakes) we could identify which glacier lakes survived or disappeared and also suppose the possible environmental causes of their disappearance (mainly in filling processes of proglacial lakes and emptying of epiglacial lakes). Thanks to a retrospective analysis we also defined which lakes appeared for the first time after the glacier retreat and when. For example, in 2006-07 the 62% of glacier lakes are located in areas previously occupied by glaciers.

Data collected through the present research can contribute to reconstruct and to interpret the spatiotemporal evolution of glacier lakes in the European Alps and to improve the knowledge about the interactions between glacier and related glacier lakes with respect to climate change, as it has been done in other regions of the world (Tartari & alii, 2008; Gardelle & alii, 2011; Salerno & alii, 2012; Hanshaw & Bookhagen, 2014; Salerno & alii, 2014; Emmer & alii, 2015; Zhang & alii, 2015;).

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